THE ENERGY INDEX OF THE CIRCULATORY SYSTEM.

By Joseph H. Barach, M.D.,
PITTSBURGH, PENNSYLVANIA.

Various methods of estimating the work of the heart and circulatory efficiency have been proposed from time to time. Some were based upon experimental and laboratory proof, others upon clinical observations, and yet out of the many there is not one that is generally accepted as being better than the rest. All of which, I believe, goes to show that up to the present time, for clinical purposes, the problem has not been approached from a correct stand-point, and has not been solved.

Strassburger[1] believed that the pulse pressure divided by the systolic pressure indicates the vascular resistance and the work of the heart. His far-reaching conclusions, however, were opposed by Sahli.[2]

Tigerstedt[3] proposed the formula P.P.MP.R. velocity, and the P.P.MP.R. efficiency of the heart as a pump.

This formula is the same as Strassburger's, and, therefore, has the same limitations.

In 1911 Goodman and Howell,[4] following the work of Tornai[5] and of Fisher,[6] constructed a formula based upon the assumption that the first and fourth phase of the auscultatory method indicates cardiac weakness, and the second and third phase indicate cardiac strength. Their method consisted in determining the percentage relation of the C. W. phase and the C. S. phase to percentage of the pulse pressure. If the C. S. were greater than the C. W., then compensation was considered good, and *vice versa*. The method has been applied clinically and found wanting.

In 1913 Stone[7] proposed a method of estimating the heart's work. The assumption of Stone was that normally the pulse pressure constitutes 50 per cent. of the D. P., and that whenever the pulse pressure is over 50 per cent. of the D. P., then the increment represents cardiac overload.

I show here that in a series of 742 normals the P. P. may constitute anywhere from 20 per cent. to 80 per cent. of the diastolic pressure in 80 per cent. of the cases; and while the average of the figures is 50 per cent., yet it does not at all hold true that in the normal person the P. P. equals 50 per cent. of the D. P.

[1] Arch. f. klin. Med., 1905, lxxxv.

[2] Münch. med. Wchnschr., 1903, No. 47.

[3] Swan, John M., Arch. Int. Med., February 15, 1915, xv, No. 2, p. 269.

[4] Ibid. [5] Ibid. [6] Ibid.

[7] Clinical Significance of High and Low Pulse Pressure, with Special Reference to Cardiac Load and Overload, Jour. Am. Med. Assn., October 4, 1913, p. 1256.

TABLE I.—RELATION OF PULSE-PRESSURE TO DIASTOLIC PRESSURE IN SEVEN HUNDRED AND FORTY-TWO NORMAL PERSONS.[1]

5 to 10	2			
10 to 20	18			
20 to 30	68			
30 to 40	111			
40 to 50	122	249 cases	461 cases	597 cases
50 to 60	127	33%	62%	80%
60 to 70	101			
70 to 80	68			
80 to 90	55			
90 to 100	25			
100 to 110	29			
110 to 120	3			
120 to 130	3			
130 to 170	10			
Total	742			

We may note that the greatest number of cases do occur near the 50 per cent. mark, and if we were to strike an average it would be close to 50 per cent., yet this would be far from representing the actual truth. These tables show there is a wide range both above and below the 50 per cent. mark in normal individuals. Our findings here warrant only a statement that the pulse pressure equals from 20 to 80 per cent. of the diastolic pressure in about 80 per cent. of the cases. And this is where we stand today. Certainly it cannot be said that any of the above methods have withstood critical investigation. There is no known method which satisfactorily indicates the amount of work which the heart or the cardiovascular system is performing; nor when the work thrown upon the circulatory system is becoming greater than its functional capacity. Nor do we have a means of measuring accurately the total work of the circulatory system and the amount of energy expended in the performance of that work. It seems, then, that we must approach this problem by another route; and such is my present purpose.

In 1914 I[2] presented a method of estimating the activity of the cardiovascular system. The purpose of this method was to indicate the expenditure of energy by the circulatory system in the act of maintaining the circulation, and it was based upon a calculation made from the three measurable factors of the arterial circulation. I wish to emphasize the fact that in this method we are dealing only with measurable factors and not inferences, such as velocity, work of the heart, functional capacity, etc.

However much one's experience may have taught him of the condition of the circulatory system, of the degree of its activity, and of its efficiency, nevertheless the all-important clinical evidences

[1] Barach and Marks, Blood-pressures, Arch. Int. Med., April, 1914, xiii, 648–655.

[2] Barach, Joseph H., The Energy Index, Jour. Am. Med. Assn., February 14, 1914, lxxii, 525.

relative to the arterial circulation which one may record for the understanding of another are the systolic and diastolic pressures and the pulse rate.

When we go beyond these evidences in attempting to measure such activities as the blood flow, the cardiac output, functional capacity of the heart, the cardiac load, etc., we find ourselves in the realm of speculation. And while it would be highly desirable indeed to be able to make such measurements, nevertheless it has been amply proved that our present-day methods are insufficient for such purposes.

Measurable Factors in the Circulation. At the present time our clinical methods are almost entirely limited to the determination of the systolic and diastolic pressure and the pulse rate, and these observations may be made with a minimum of apparatus and technic. With the mercury manometer and by the auscultatory method we can determine the values of these three factors with certainty and accuracy.

Much has been said and written of the pulse pressure; it has been used as a basis for calculation of the blood flow, the work of the heart, cardiac load and overload, etc.; but after numerous observations of my own and a *résumé* of the work done by others, I am inclined to believe that up to the present time at least the estimation of pulse pressure has added comparatively little to our total knowledge of the circulation. I do believe that we will still gather some facts by studying the pulse pressure under certain conditions, but up to the present this has not yet been accomplished. The important factors are the systolic pressure which indicates the ventricular force, the diastolic pressure which indicates the intravascular tension during diastole, and at the same time the peripheral resistance, and the pulse rate which designates the frequency with which the heart must contract to maintain the flow of blood as required by the organism. It may be stated as an axiom that no alteration in function of the circulatory system can take place, but there is a change of values or a readjustment in more than one of the three factors. These three factors are interdependent, one upon the other, and are constantly adapting reciprocally to one another according to the needs of the organism. The relation of systolic and diastolic pressure and pulse rate, one to the other, may well be illustrated by comparison to a triangle of fixed area in which if one line of the triangle is altered the other two are likewise changed. I illustrate this by shaping a piece of cord or a chain in the form of a triangle, by which is readily seen that changing the length of the base or either one of the sides of that triangle alters the value of the other two sides.

Adaptation of Maximum and Minimum Pressures and Pulse Rate. That there is a constant adaptation of each factor in the triad to the others is shown in the following results obtained from

a series of 24 cases. These observations were made in young men previous to a race of 24.85 miles. The young men were in extraordinarily good physical condition. We found that change of posture from horizontal to erect caused an increase of pulse rate in 14, a diminution in 4 and no change in 6. The maximum pressure was diminished in 11, unchanged in 3, and increased in 10. The minimum pressure was diminished in 9, unchanged in 9, and increased in 6. After the race, in which 19 out of the 24 finished, when the blood-pressure had fallen fully 20 per cent., and the subjects were in a state of exhaustion, upon change from horizontal to erect posture the pulse rate was increased in 18 and unchanged in 1. The maximum pressure was diminished in 11, unchanged in 3, and increased in 5. The minimum pressure was diminished in 7, increased in 6, unchanged in 4, and not obtained in 2.

The conclusions from the above observations are that whether the vascular tone be of the highest attainable state of efficiency or in a state of exhaustion, each element in the triad is a constantly varying factor, and that whether the cardiovascular tone be good or poor, the manner of reaction appears to be the same, at both times being accomplished by a readjustment of all the factors. It appears, therefore, that these observations bear out the previously stated axiom.

Adaptation of the Triad in Cardiac Hypertrophy. Another example of the accommodation of these factors, one to the other, is to be found in the following figures based upon observations in a series of athletes who presented the pure form of cardiac hypertrophy—the athletic heart. In this series of cases in which we knew that the left ventricle was enlarged because of its appearance behind the fluoroscope and by physical examination, and in which the systolic pressure was increased, we found that the pulse rate was slower than in a series of subjects who had not undergone systematic physical training. Whereas, in a series of cases in which the maximum pressure ranged between 100 and 120, the average pulse rate was 79 in 29 non-trained men and 76 in 12 trained men. In a series in which the maximum pressure ranged from 130 to 140 the pulse rate was 82 in 22 non-trained men and 72 in 7 trained men.

From this we see that when the left ventricle becomes hypertrophied and the ventricular force and output are greater, the conserving forces of the body will cause a slowing of the pulse rate.

By a slowing of the pulse rate the total expenditure of energy per unit of time in the hypertrophied heart was not greater than in the non-hypertrophied heart. As measured by the S. D. R. index the average energy expenditure in the 100 to 120 non-hypertrophied cases was 15,908 mm. Hg. per minute, and in the hypertrophied cases 15,706 mm. Hg.

In the cases in which the maximum pressure ranged from 130 to

140 mm. Hg. the energy index of the non-hypertrophied cases was 17,960 mm. Hg. and 16,856 mm. Hg. in the hypertrophied cases, showing that whether the heart is hypertrophied or not, the normal organism requires but a certain fulfilment of function, and that the hypertrophy is necessary only for the occasion of greater effort. Along with the other features which this method of calculation seems to bring out, these foregoing evidences point clearly to the fact that if we are to come to a correct conclusion as to the activity of the circulatory system we must take into our calculation the complete triad.

THE S. D. R. INDEX. Since the evidences upon which we may depend are included in the triad formed by the systolic pressure, diastolic pressure, and pulse rate, it seems that a calculation based upon this triad must give us the desired information relative to the activity of the arterial circulation. Such is the purpose of the S. D. R. index.

The premise here is that each pulse beat is composed of two successive phases—the systolic phase and the diastolic phase—and that the total force exerted with both phases is what constitutes the entire beat. The systolic pressure in an artery is that amount of force exerted with the systole which is capable of lifting a column of mercury to a certain height. The diastolic pressure is the force exerted by the intravascular tension during the diastolic phase. For example, in a certain case the systolic force (kinetic energy) is equal to the lifting of 120 mm. of Hg. and the diastolic force (kinetic energy) is equal to 80 mm. of Hg. pressure. Therefore, with one pulse beat the measurable quantity of force (kinetic energy) is equal to the lifting of 200 mm. Hg., and with 72 such pulse beats the force would be 72 × 200 or 14,400 mm. Hg.

For clinical interpretation we may presume that the systolic pressure represents the effort of the arterial system, and the pulse rate represents the effort of the heart, as a whole, to maintain the circulation. Or we may assume that we are simply trying to determine the degree of effort expended by the circulatory system in carrying on the circulation to maintain the needs of the organism. For that purpose we note the energy of the systole, of the diastole, and how many times per minute that much energy is expended. We do not deal here with absolute results, the product of our calculation does not quantitatively measure, but it does indicate clearly the expenditure of energy per unit of time.

THE NORMAL S. D. R. INDEX. If we are to use this method of estimating the energy expenditure per unit of time we must establish the values of normal persons. For that purpose the following table has been constructed. This table is based upon 250 normal individuals in whom the pressure ranged within what we consider the extremes of normal limits. Here are included only those cases in which the minimum pressure did not exceed 100 mm. Hg. and

the pulse rate did not exceed 90 beats per minute. With an upper limit of about 150 mm. Hg., I believe we are within the normal bounds.

TABLE II.—TOTAL ENERGY INDEX IN TWO HUNDRED AND FIFTY NORMAL PERSONS.

100	3	cases average	13541	mm. Hg.	per minute
100 to 120	42	" "	15918	"	"
120 to 130	123	" "	16902	"	"
130 to 140	44	" "	17690	"	"
140 to 150	22	" "	18527	"	"
150 to 160	16	" "	21076	"	"
	250				

I therefore believe that in normal persons, as estimated by the energy index, that the pressure does not exceed 20,000 mm. Hg. per minute.

Variations in Energy Expenditure as Detected by the Index. Here it is my purpose to show that the maximum pressure reading alone conveys practically no information concerning the activity of the circulation.

The following table is based upon observations made upon a group of 289 young men between the ages of fifteen and thirty years. I have chosen the extreme cases of each group, and show that while Case A and Case Z both had the same maximum arterial pressures, the total energy expenditures at the time of examination was very much greater in Case Z than in Case A. This difference of activity in the circulation of these cases was quite obvious. Some of these young men entered the examination room anxious-looking, pale, with apex impact prominent, and at first glance it could be seen they were in a state of mental and nervous excitation with the usual effects upon the cardiovascular system.

The energy index in these cases showed this increased action, whereas the maximum pressure reading indicated nothing of what was actually going on at that time.

TABLE III.—TABLE OF TOTAL ENERGY INDEX IN TWO HUNDRED AND EIGHTY-NINE CASES.

Group.	No. of cases.	Maximum blood pressure, mm. Hg.	Extreme instances. Case.	Maximum.	Minimum.	Pulse.	Energy index, mm. Hg. per min.
1	41	From 110 to 120 .	A	115	52	72	12,024
			Z	110	88	124	24,552
2	99	120 to 130 .	A	124	68	68	13,056
			Z	125	100	120	27,120
3	76	130 to 140 .	A	138	90	64	14,592
			Z	132	118	132	33,000
4	43	140 to 150 .	A	142	85	60	15,436
			Z	148	98	120	29,520
5	26	150 to 160 .	A	150	90	76	18,240
			Z	150	115	88	27,440
6	4	160 to 170 .	A	164	110	68	18,632
			Z	162	80	120	29,040

EFFECT OF PHYSICAL EXERTION AS INDICATED BY THE S. D. R. INDEX. During the past year, with the assistance of Dr. W. L. Marks, of the Carnegie Institute of Technology, I made a rather extensive series of observations upon the effect of graduated amounts of physical exertion upon the circulatory system and calculated the results by the S. D. R. index. This work will be published later in detail, but for the present purpose I cite an instance of the results obtained. The exercise consisted of running to the time of a metronome at the rate of 152 steps per minute for a period of one minute:

	Case A.				Case B.			
	Pulse.	Systolic.	Diastolic.	Index, mm. Hg.	Pulse.	Systolic.	Diastolic.	Index, mm. HG.
Before . . .	72	104	78	13,104	100	120	85	20,500
15 seconds after	92	132	90	20,424	132	165	95	34,320
5 minutes after	80	120	80	16,000	108	130	90	23,760

These figures in all cases show (1) that each one of the triad is a constantly varying factor; (2) they show that with the exertion there came an increased demand upon the circulatory system, and that as this demand ceased the activity lessened and returned toward the normal, sooner in some cases than in others, and finally the figures show the degree of reaction on the part of the circulatory system.

By observing the effects of definite amounts of physical exertion upon the circulatory system, as indicated by the S. D. R. index, and by noting the degree and duration of the increase, we have come upon a method of estimating the circulatory efficiency of our subjects. This we will treat fully in a later consideration of this subject.

SUMMARY. 1. It is an axiom that changes in the activity of the circulatory system are accomplished by the adjustment of three factors: the maximum pressure, minimum pressure, and pulse rate.

2. That since these are measurable factors a calculation based upon this triad should indicate the total energy expenditure of the circulatory system.

3. The product of such a calculation, which I termed the energy index, under normal conditions represents a kinetic force per minute equal to not over 20,000 mm. Hg. pressure.

4. In the S. D. R. index or the energy index we have a method which is based upon the three measurable factors of the circulation, and one which indicates per unit of time the total expenditure of energy by the circulatory system in the performance of its functions.